Origins of the Kuroshio and Mindanao Current

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LONG-TERM GOALS

The boundary currents off the east coast of the Philippines are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC). The partitioning of the flow into the Kuroshio and MC is an important observable. Quantifying these flows and understanding bifurcation dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave climate. This study incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao current.

OBJECTIVES

The objectives of this program include quantifying flows and water properties, improving understanding of the dynamics of a bifurcation region, and establishing predictability of the three major currents in the region. The observational approach will have two major thrusts: (1) quantifying the fluxes of mass, heat, and salt in the NEC, Kuroshio, and MC, and (2) establishing Lagrangian patterns of flow. To quantify the seasonal cycle and to obtain an initial measure of interannual

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variability, these observations will be sustained over a three-year period. The bifurcation region is an interesting target, but the stagnation point of a turbulent flow is not an easy quantity to observe. The sustained observations will provide a test for models of the regions, and at the same time will be available for assimilation in models.

APPROACH

The proposed observing system employs a suite of complementary platforms to meet the challenges posed by this vast, highly variable study area. Guided by previous studies and by directed analysis of historical data, long-endurance autonomous gliders will be tasked to collect repeat occupations of key sections across the NEC, MC and Kuroshio. Because previous observational programs show that the Kuroshio sometimes reaches nearly to the coast, where glider operations can be difficult and risky, small arrays of moored instruments will augment glider sections to resolve the nearshore regions. Drifters and floats will be used to illuminate the pathways by which the NEC ultimately forms the Kuroshio and MC. Numerical efforts will aid interpretation and explore the predictive capabilities of regional models.

WORK COMPLETED

Gliders

Gliders are being used to observe the NEC and the Mindanao Current. Two Sprays are deployed from Palau every 4-5 months, one that proceeds northward across the NEC, and one that heads westward towards the MC. Operations commenced in June 2009 under a previous grant, and have continued uninterrupted. The data set includes 18 glider missions, two of which are active at this time. To date, we have completed 15 crossings of the Mindanao Current, and 13 sections across the NEC (Figure 1). In total, the gliders have done 8234 dives, and covered over 35,427 km in 2103 days. The next turnaround is scheduled for January 2013.

Analyses so far are focusing on two issues: (1) flows in the NEC and Mindanao Current, and (2) submesoscale variability. Geostrophic currents through each section are calculated, referenced using the glider-observed depth-average velocity. The core of the Mindanao Current is found to be as strong as 1.5 m/s southward, with northward flows in the Mindanao Undercurrent approaching 1 m/s. The mean NEC has been established by the 3 year of measurements (Figure 2). Westward flow is confined mainly to the upper 300 m, and is strongest just north of Palau, where it peaks at about 0.5 m/s. Two cores of eastward flow are apparent deeper than 300 m, one north of Palau and a second at 13°N. Layers of high thermohaline variability are observed on isopycnals in the salinity maximum near 100 m, and in the salinity minimum near 400 m. The persistence of these layers will be a subject of continuing analysis. A study of these layers as they exist in the Kuroshio was published in Oceanography magazine (Rudnick et al. 2011). Graduate student Martha Schonau has joined our group, and her doctoral research will focus on Spray glider data from OKMC.

The use of gliders to observe high frequency internal waves has been investigated using data from previous deployments in the Luzon Strait region. The vertical velocity is deduced from fluctuations in the gliders' flight path. By averaging over several glider deployments over a year, the existence of internal waves traveling eastward into the Pacific from the Luzon Strait was ascertained. These waves had been predicted theoretically, but this was the first in situ observational evidence of their presence. A paper describing this work is under revision for publication in the Journal of Geophysical Research (Rudnick et al, 2012).

Floats
Ten floats were deployed in August 2011 from the Japanese R/V Mirai. Analysis of these data is in collaboration with Bo Qiu of U. Hawaii. Initial analysis is using these floats in conjunction with the rest of the Argo float array, with a focus on the NEC. Data from these floats are processed through the Argo system, and are made available through GTS to modeling centers including NAVO. An additional 20 floats obtained through a DURIP will be deployed during the first quarter of 2013 from the R/V Mirai.

Drifters
The scientific objectives of the drifter program are to map the seasonal surface circulation in the South Philippines Sea and to understand the seasonal migration of the separation point in the western boundary of the North Equatorial Current. To enhance the historical near surface current data in the study area, deployments of surface drifters from the merchant vessels from Kaohsiung to eastern Australia were performed. Professor Ruo-Shan Tseng at National Sun Yat-sen University is a local contact point in Taiwan to store, prepare and deliver the drifters to the ship. The deployments were continued in 2011 and six deployment cruises (9 drifters for each deployment) have been made successfully. The Hyundai Shipping Co. cancelled the regular route from Kaohsiung to Australia, i February 2012 because of global recession and five deployments were skipped starting from February, 2012. Fortunately drifter deployments by the Global Drifter Program supplemented this study (Figures 3-4). We deployed a total of 54 drifters since October, 2011 and 8 drifters failed on deployment (Figures 3-4). In the winter monsoon, the Kuroshio formation was well defined in the Philippine Sea (Figure 3) but the formation of the Kuroshio was not evident during the summer monsoon. As shown by Centurioni *et al*. (2004), many drifters entered into the South China Sea during the winter monsoon.

Modeling
MITgcm forward and adjoint modeling studies of the OKMC region have continued, and we have started 4D-Var state estimation using satellite SSH and SST with temperature and salinity profiles from floats and gliders. The 1/6° regional domain is still in use, and T-S adjustments of the HYCOM initial conditions and boundary conditions are still under study. The first paper studying the dynamical sensitivity of western boundary transport as calculated by the model adjoint is in press at JPO, and we are now studying the problem at finer space and time scales using the new model runs.

Two global fine resolution ocean general circulation models forced with synoptic atmospheric reanalysis fluxes are used to address project goals. The models are: data assimilative global 1/12° Hybrid Coordinate Ocean Model (HYCOM) and a newly completed global 1/10° Los Alamos Parallel Ocean Program (POP) simulation. Both resolve mesoscale eddies in the tropical northwest Pacific. The HYCOM simulation was forced with Navy Operational Global Atmospheric Prediction System (NOGAPS) fluxes, and the output consists of daily state variables and atmospheric forcing for the period 2006-2010. The POP simulation was forced with Co-ordinated Ocean-Ice Reference Experiment 2 (CORE2) interannually varying atmospheric fluxes (IAF; Large and Yeager, 2009) for the period 1990-2007. CORE2 is based on NCEP reanalysis only for the near-surface vector wind, temperature, specific humidity, and density, and on a variety of satellite-based radiation, sea surface temperature, sea-ice concentration, and precipitation products (Large and Yeager, 2009). This POP simulation was initialized from a three-decade spun-up ocean state where POP was forced with CORE climatological forcing (Maltrud et al., 2010). Daily-averaged state variables and covariance terms needed for eddy flux calculations, and daily atmospheric forcing terms were archived in our region of interest for the years 1994-2007. This is a one of a kind set of output in that variables have been

archived for such an extended period at a very high archiving frequency, allowing a thorough investigation of both local and remote forcings that cause variability on temporal scales from several days through interannual.

Our focus this past year was the analysis of the long POP simulation. The veracity of the mean and variability of the surface circulation in our region was examined through comparisons with observations *i.e.* mean dynamic ocean surface topography (Maximenko et al. 2009) and AVISO sea surface height anomalies (SSHA). Next we examined the partitioning of flow into the Kuroshio and Mindanao Currents and quantified the seasonal and interannual migration of the North Equatorial Current (NEC) bifurcation off the Philippines. To understand causality between SSH variability in the KC (MC) offshore of the northern (southern) end of the Philippine Island chain and that further offshore to the east of the Philippines, we calculated coherence-squared/phase relationships for various frequency bands. For interannual frequencies the coherent signals represented Rossby waves. For 100d, significant signals were found along the paths of the emerging MC and the KC as these currents approached the Philippine coast and turned to become coast parallel as shown by the velocity fields. Further analyses are now underway to better understand the cause of these 100d coherent signals.

RESULTS

With OKMC started just over one year ago, the most signficant results lay in the future. At this stage, the following results are most evident.

- Strong stirring is evident in the salinity extrema. This feature is consistent with the relatively young age of the water in the extrema relative to the inflection level between.
- The mean NEC is firmly established, with the strongest flows in the south and near the surface. An eastward flowing undercurrent beneath the NEC is a robust feature in the mean.
- The sensitivity of SSH and transport to wind stress curl spreads to the east going backwards in time, but advection is important. The influence of the model state on the gradients (nonlinearity) is more apparant at these shorter scales, and nonlinearity clearly increases poleward. The contribution of the coastal waveguide is smaller than that of the propagating Rossby waves, but it is still important, and points up the relation to island rule theory and its generalizations.
- From historical and new drifter observations, a strong westward Winter Subtropical Current (WSC) is found in the Northwestern Pacific between 18°N and 23°N. The decadal strengthening of negative wind stress curl in the subtropical area north of Hawaii and west of 150°E is the main forcing of this newly observed seasonal current. The annual fluctuation of the WSC transport is reflected in the springtime Kuroshio transport in the south of Japan. The annual variation of the transport by WSC is also correlated with the North Pacific Index (NPI), which represents the strength of the Aleutian Low before the 1988/89 climate shift, but the correlation with teleconnection patterns or climate indices is not found after the 1988/89 shift. A paper describing these results was submitted to Geophysical Research Letters (Lee et al, 2012).

IMPACT/APPLICATIONS

- The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows. Gliders are showing potential for the sustained observation of major ocean currents.
- The value of drifters for regional oceanography is being further established through this program.
- The boundary current is found to be sensitive to local and basin-wide wind stress, providing a target for predictive models.

RELATED PROJECTS

Related projects include and ongoing Early Student Support grant and a completed DURIP. This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

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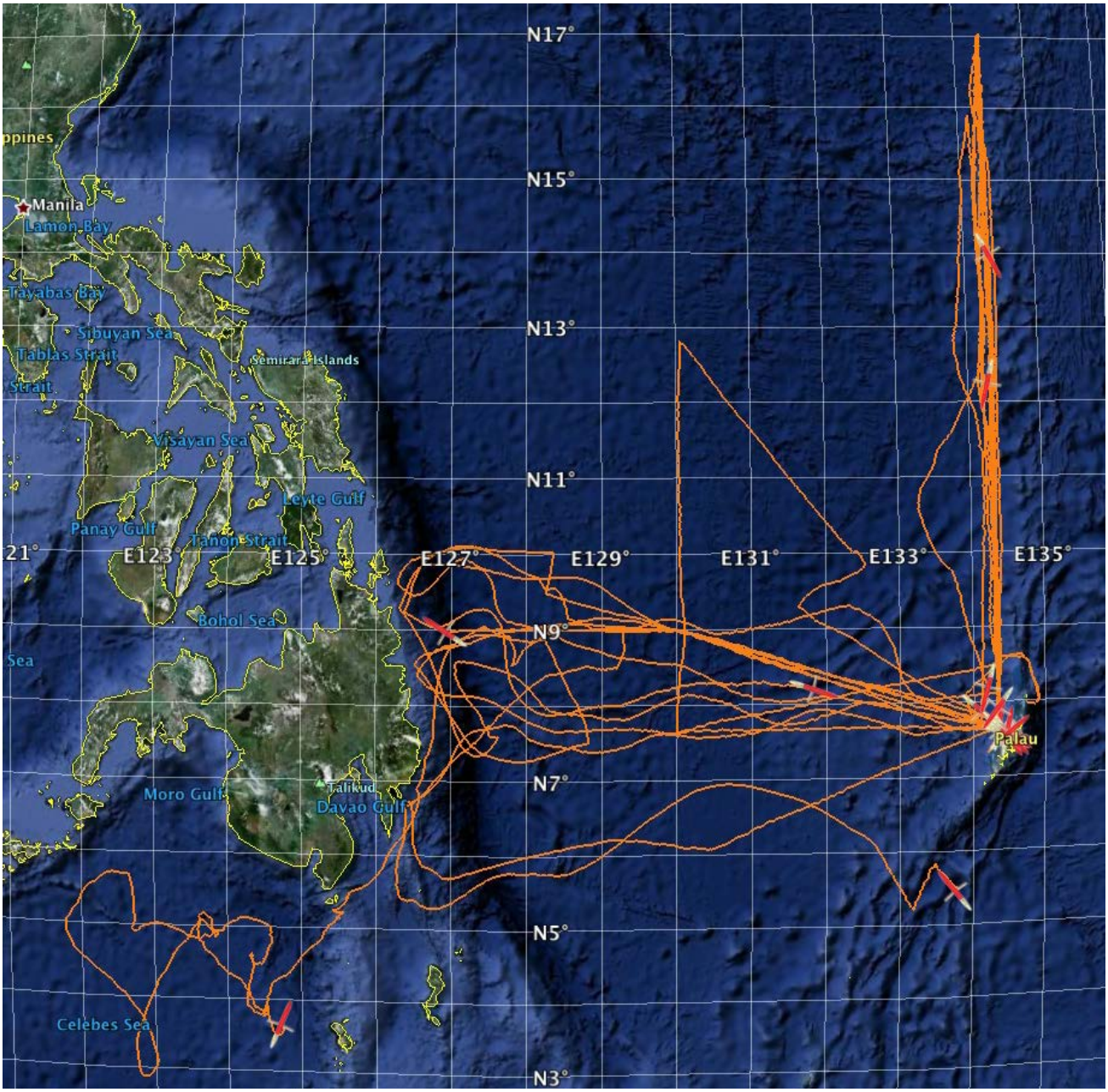

Figure 1. Spray glider trajectories for all missions since June 2009.

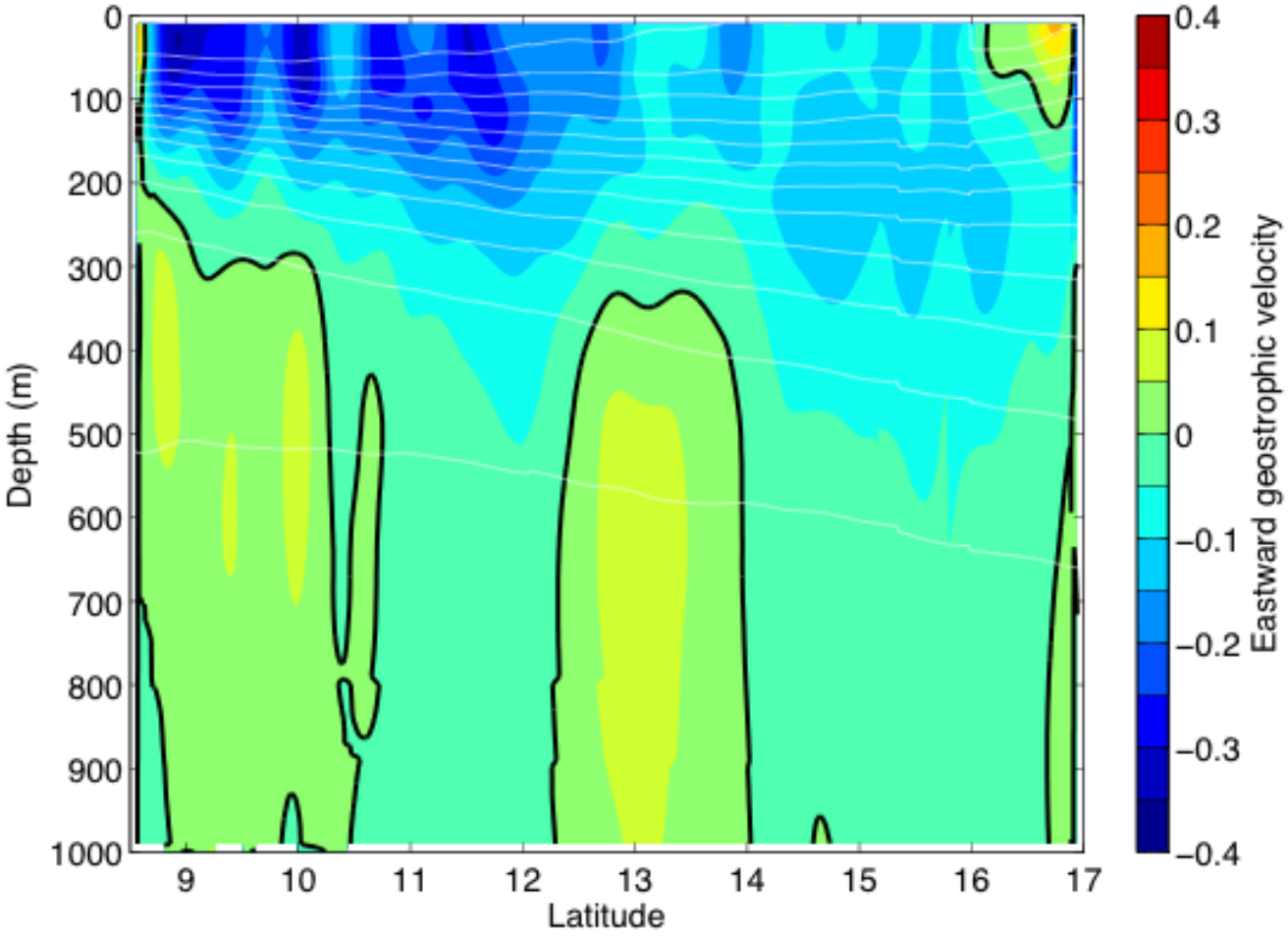

Figure 2. Mean eastward geostrophic velocity from glider sections across the North Equatorial Current, along 134°20'E. The geostrophic flow is referenced to the depth-average current directly measured by gliders. These direct observations of current are essential to reveal the eastward undercurrents beneath the NEC.

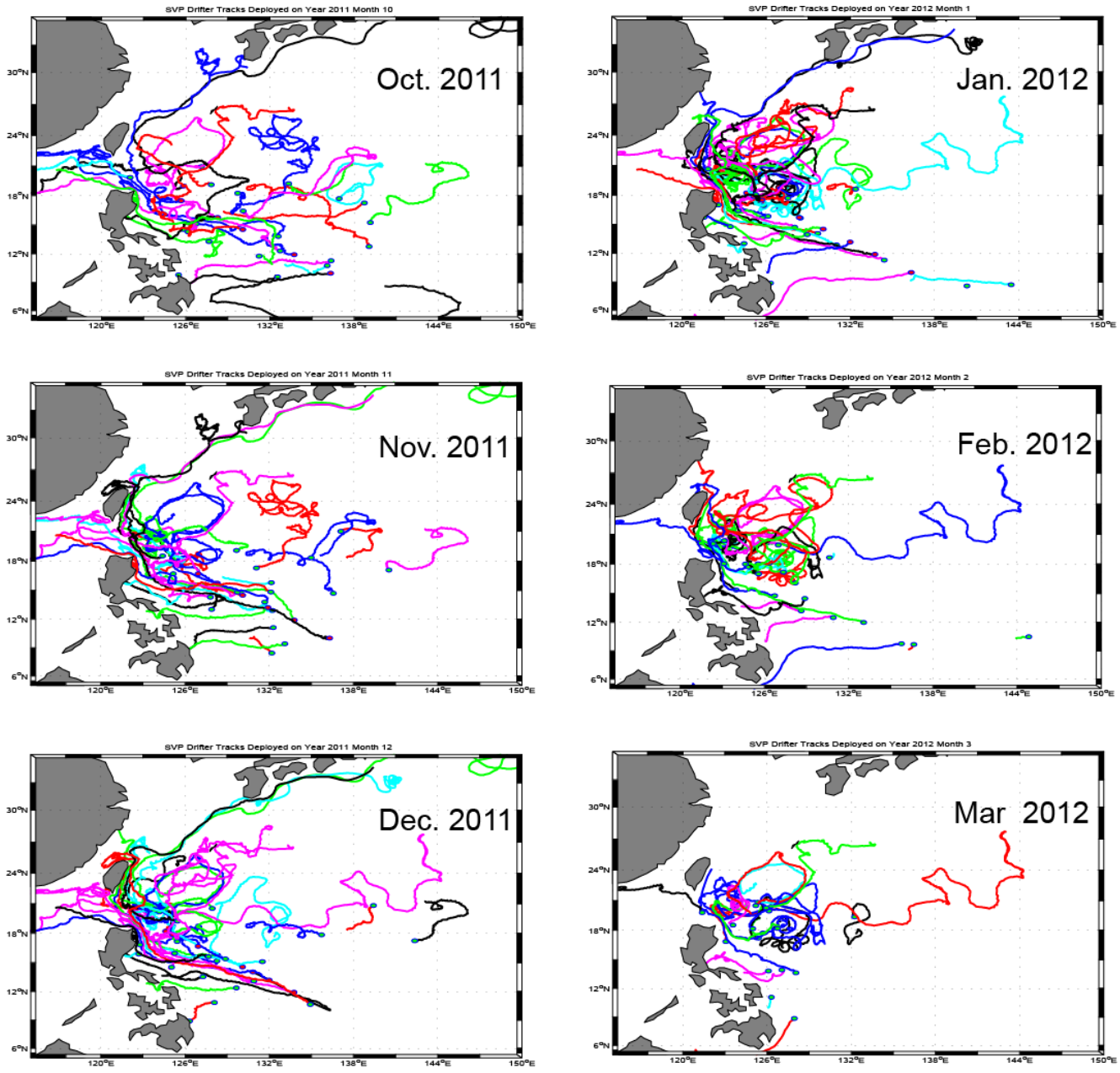

Figure 3. Monthly drifter tracks from October, 2011 to March, 2012 in the study area. Red dots represent OKMC deployments and green dots represent either existing drifters or GDP deployments.

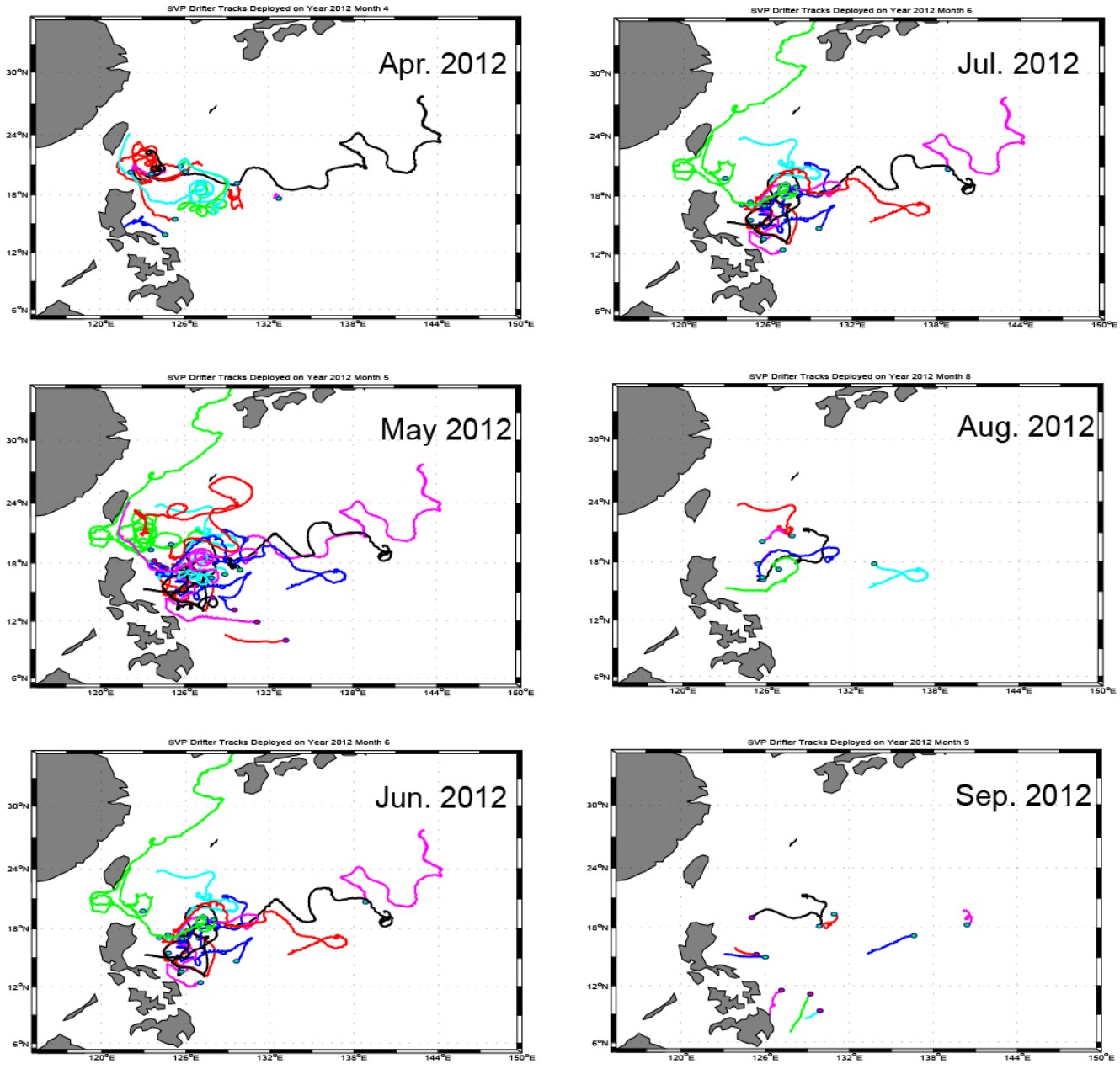

Figure 4. Monthly drifter tracks from April, 2012 to September, 2012 in the study area. Red dots represent OKMC deployments and green dots represent either existing drifters or GDP deployments.